

An Eight-Month Climatology of Marine Stratocumulus  
Cloud Fraction, Albedo, and Integrated Liquid Water

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#### INTRODUCTION

As part of the FIRE/ETO program, extended time observations were made at San Nicolas Island (SNI) from March to October, 1987. A small ground station was installed at the NW tip of SNI, which is dominated by marine flow most of the time. Hourly averages of air temperature, relative humidity, wind speed and direction, solar irradiance, and downward longwave irradiance were recorded. The radiation sensors were standard Eppley pyranometers (shortwave) and pyrgeometers (longwave). San Nicolas Island also served as the focus of the first stratocumulus IFO during July, 1987.

The SNI data have been processed in several ways to deduce properties of the stratocumulus covered marine boundary layer (MBL). For example, from the temperature and humidity the lifting condensation level, which is an estimate of the height of the cloud bottom, can be computed. A combination of longwave irradiance statistics (mean and standard deviation) can be used to estimate fractional cloud cover. We will also describe an analysis technique used to estimate the integrated cloud liquid water content (W) and the cloud albedo from the measured solar irradiance. In this approach, the cloud transmittance is computed by dividing the irradiance measured at some time by a clear sky value obtained at the same hour on a cloudless day. From the transmittance and the zenith angle, values of cloud albedo and W are computed using the radiative transfer parameterizations of Stephens (1978). These analysis algorithms have been evaluated with 17 days of simultaneous and colocated mm-wave (20.6 and 31.65 GHz) radiometer measurements of W and lidar ceilometer measurements of cloud fraction and cloudbase height made during the FIRE IFO. The algorithms are then applied to the entire data set to produce a climatology of these cloud properties for the eight month period.

#### SHORTWAVE CLOUD/RADIATION PARAMETERIZATION

Solar radiative transfer through stratocumulus clouds can be computed with reasonable accuracy given a specification of the appropriate microphysical variables (optical thickness, single scattering albedo, asymmetry factor, and zenith angle). For our application, we wish to use measurements of a particular bulk cloud radiative transfer property (transmission coefficient) to deduce the integrated liquid water content and the albedo (solar reflection coefficient) of the overlying cloud. In order to streamline this process, we have chosen to use a radiative transfer parameterization (Stephens, 1978), rather than a full blown multiband radiative transfer code. From a measurement of cloud transmission coefficient and a specification of solar zenith angle, we obtain from the parameterization the optical thickness and the cloud albedo. A second parameterization relating optical thickness to integrated liquid water is used to compute W.

A detailed description of the algorithm and an evaluation using the FIRE/IFO data has been previously described (Fairall et al., 1988) so we will summarize here. Values of  $W$  estimated from the solar transmittance are on average 65% of the values derived from the microwave radiometer. A log-log linear regression yields a slope very near one with a correlation coefficient of 0.87. The rms scatter about the regression line represents about 35% variability in the value of  $W$ . In pondering the disagreement between the two measurements, we feel the best evidence suggests that the microwave radiometer values are quite accurate. It is possible that the actual cloud droplet concentrations were substantially less than the assumed value of  $100/\text{cm}^3$ . Also, Coakley and Snider (1989) have suggested that nonlinear effects could affect our result. Using a Taylor expansion of the transmission coefficient, we can relate the mean water content to the mean transmission coefficient by

$$\langle W \rangle = W(\langle \text{Tr} \rangle) [1 + S (\sigma_w / \langle W \rangle)^2] \quad (1)$$

The dimensionless nonlinear sensitivity coefficient,  $S$ , is given by

$$S = -(1/2) [\partial^2 \text{Tr} / \partial (\ln(W))^2] / [\partial \text{Tr} / \partial (\ln(W))] \quad (2)$$

We have used the Stephen's parameterization to evaluate (2) by numerically computing finite difference first and second derivatives at various values of zenith angle and mean integrated liquid water content. As defined here,  $S$  is positive over the range of values of  $W$  of interest here (it becomes negative at very small values of  $W$ ), so small scale cloud variability tends to cause us to underestimate  $W$  from the mean transmission coefficient. We have used the high speed time series of  $W$  from the microwave radiometer to compute  $\sigma_w$  on a one hour time scale. A typical value for  $\sigma_w / W$  is on the order of 0.25. Larger values are observed for smaller  $W$ , but this is compensated by the decrease in  $S$ . Using a value of  $S=1.2$  for  $W \approx 50 \text{ g m}^{-2}$ , we find that nonlinear effects have reduced the pyranometer estimates of  $W$  by about 3%. This appears to be almost negligible, but we admit that this result is very sensitive to the value of  $\sigma_w / W$  used.

#### LONGWAVE PARAMETERIZATION FOR CLOUD FRACTION

Cloud fraction is a very thorny issue that is just beginning to receive theoretical interest in cloud models. The definition of cloud fraction is often confused by the concepts of scale. A 24 hour period of broken clouds may yield the same average cloud cover as 12 hours of solid stratus followed by 12 hours of clear skies, but on a larger scale the stratus may be considered to be part of a broken cloud field. For our purposes, we will consider cloud fraction,  $f$ , to be the fraction of time in one hour that a narrow field of view instrument in a zenith pointing mode (i.e., a lidar ceilometer) detects the presence of a cloud overhead.

Since it is well known that the downward longwave radiative flux received at the surface is substantially greater (by roughly  $100 \text{ W m}^{-2}$ ) in the presence of stratocumulus clouds versus clear skies, we decided to develop an algorithm to use the pyrgeometer time series to estimate  $f$ . We considered two approaches: (1) compute  $f$  by comparing the measured downward longwave,  $L_m$ , to anticipated values for clear,  $L_o$ , and stratocumulus conditions,  $L_s$ , and (2) compute  $f$  by comparing the standard deviation of downward longwave,  $\sigma_1$ , to  $L_o$  and  $L_s$ . The values for  $L_o$  and  $L_s$  are obtained from standard bulk models of downward longwave irradiance. In the end we chose method (2) because it was significantly less sensitive to the details of our determination of  $L_o$  and  $L_s$  at the extremes (i.e.,  $f=0$  or  $1.0$ ).

If the formulae for  $L_o$  and  $L_s$  were accurate, we would postulate that a reasonable estimate of the cloud fraction would be given by  $f=(L_m - L_o)/\Delta$  where  $\Delta=L_s-L_o$ . However, these simple models do not take in enough information to describe a large part of the variability of  $L_o$  and  $L_s$  (Siegel and Dickey, 1986). In an effort to obtain a more reasonable estimate, we decided to use the variance of the measured radiation,  $\sigma_1^2$ . With a bit of mathematical manipulation, we can show that

$$\sigma_1^2 = \langle (L - \langle L \rangle)^2 \rangle = f(1-f)\Delta^2 \quad (3)$$

We can express the solution to (3) as

$$f = \{1 \pm [1 - (m\sigma_1/\Delta)^m]^{1/2}\}/2 \quad (4)$$

where for the quadratic form of (4) we have  $m=2$ . We have left this exponent as an adjustable parameter because of the wide field of view of the pygeometer. A comparison with the lidar ceilometer showed (Fig. 1) that  $m=1$  gives a better fit to the FIRE IFO data. Since (4) is double valued, we need a method to select which sign (+ or -) is appropriate. Here we use the measured mean irradiance; if  $L_m < L_o + \Delta/2$ , then we use the negative sign in (4). This implies that our algorithm will be most inaccurate when it yields  $f=0.5$ , where the result is critically dependent on the accuracy of the bulk formulae.

#### EIGHT MONTH STATISTICS

The system at SNI provided a continuous record of 30 minute averages of the data from Julian day 50 to 285. One period (day 142 to 154) was lost due to an extended power outage. The summer heavy stratocumulus season is apparent in the time series of weekly averaged mean cloud cover (Fig. 2) deduced from the longwave algorithm. A variety of statistics have been computed from this data base. Frequency distributions have been computed for albedo (Fig. 3a), integrated cloud liquid water (Fig. 3b), and cloud fraction (Fig. 3c). These data imply that the typical daytime stratocumulus at SNI has an integrated liquid water content of about  $75 \text{ g m}^{-2}$  and an albedo of 0.55.

An average diurnal cycle of cloud fraction for the three summer months (Fig. 4a) shows a substantial modulation of the clouds, presumably caused by the cloud absorption of solar energy. The resultant warming of the mixed layer raises the cloudbase and reduces  $W$ . Despite the limitations of the solar data we have computed average diurnal cycles for albedo (Fig. 4b). In order to broaden the part of the diurnal cycle covered, we have relaxed the restriction on solar zenith angle to permit computation for  $\mu > 0.1$ . The same analysis for  $W$  (not shown) indicates that the mean values of  $W$  appear to increase from very low values for the first three hours after sunup, which is considered to be evidence that our algorithm is not reliable if  $\mu < 0.4$ . Only the seven hours centered about local noon can be considered usable for liquid water. The albedo computation is probably reliable over the entire interval; the increased albedo at low incidence angle is expected.

It is also important to avoid overselling this approach. The algorithms developed here are considered to be most appropriate for marine stratocumulus. They have been verified against a single 17-day data set. The cloud fraction algorithm we have used is most effective as a cloud versus non-cloud indicator, and obviously will work best with very low cloudbase and solid clouds. The ceilometer is a more appropriate device for this purpose (it also yields more accurate cloudbase height than the lifting condensation level computation), but it costs an order of magnitude more than the pygeometer.

The pyranometer algorithm provides important information on cloud microphysical and radiative transfer properties, but only during the day. The microwave radiometer provides far superior performance for measuring W, but only a few systems exist in the world and their cost, compared to a pyranometer, is astronomical.

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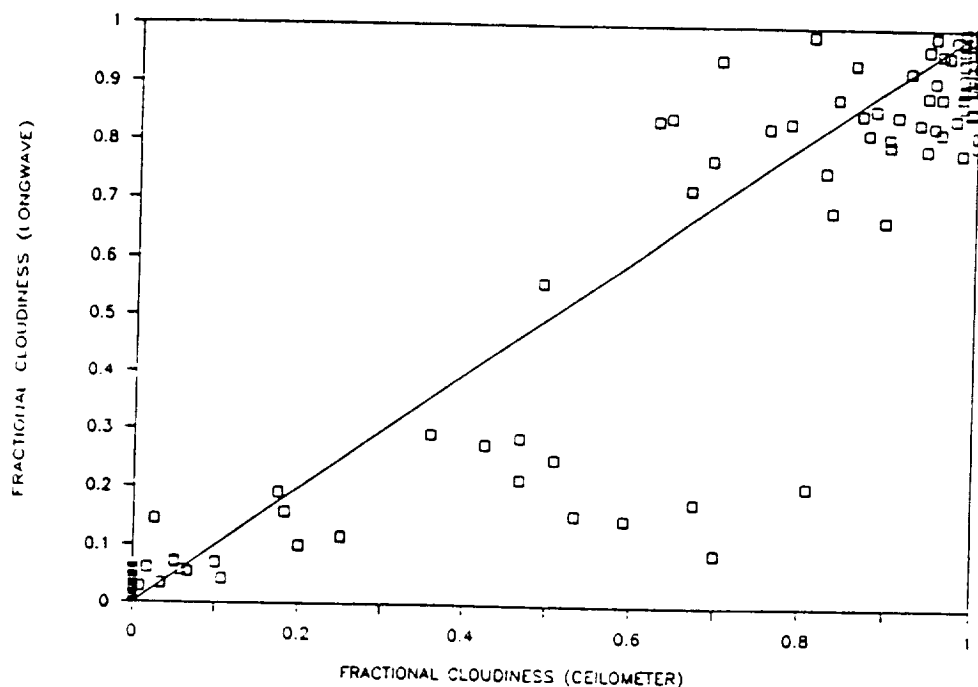


Fig. 1. Fractional cloudiness (f) estimated via (4) versus direct measurements by the lidar ceilometer during the FIRE IFO period.

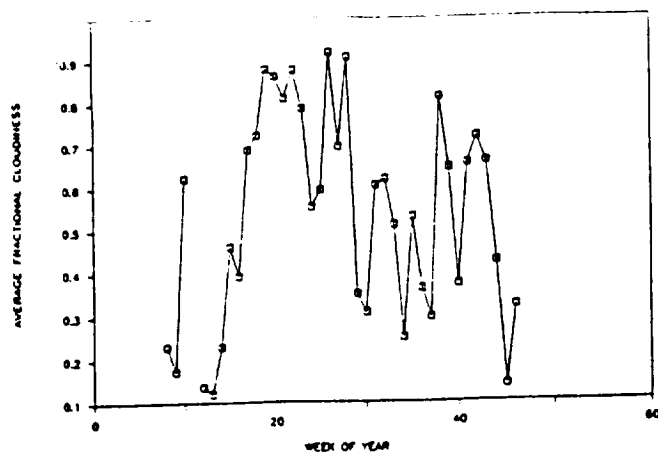


Fig. 2. Time series of weekly averaged fractional cloud cover, computed from the longwave irradiance, for the eight month data period. The stratocumulus season is evident as the high values of  $f$  in the April to September period.

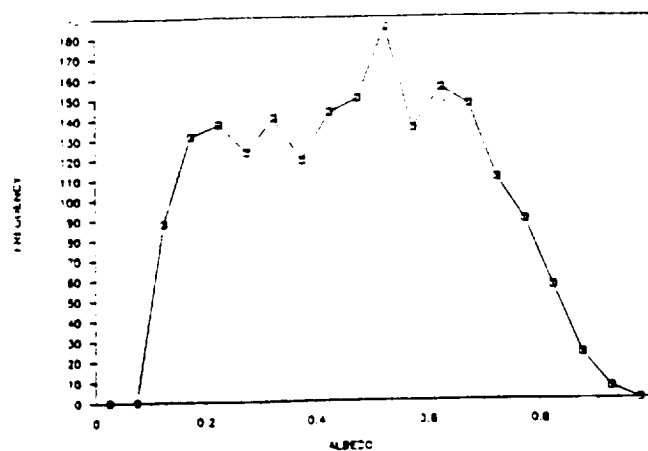


Fig. 3a. Frequency distributions of cloud albedo using the one-hour data, computed using the methods described in the text, for the eight month period.

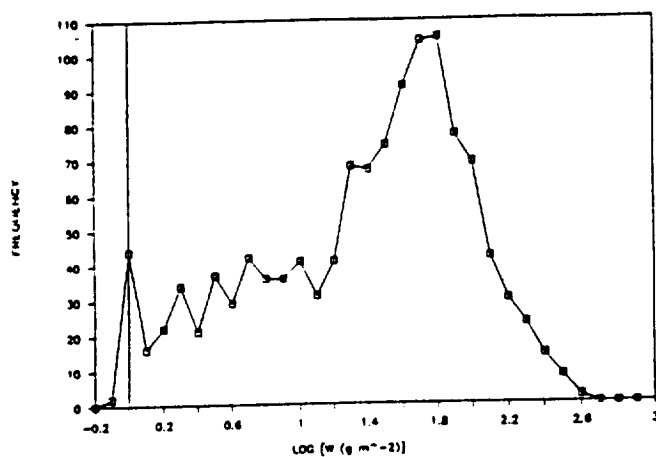


Fig. 3b. As in Fig. 3a but for integrated cloud liquid water content,  $W$ .

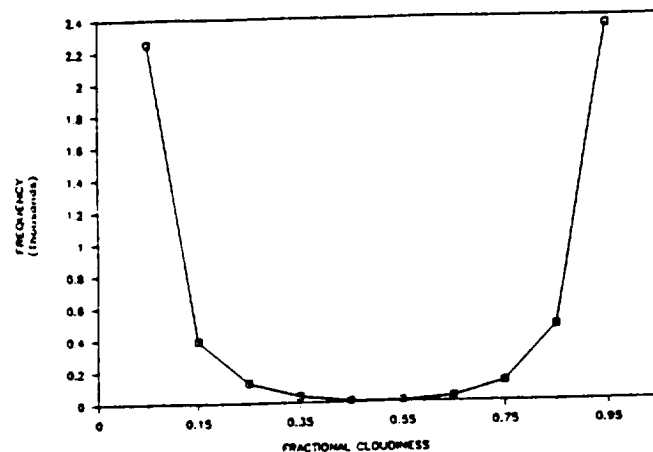


Fig. 3c. As in Fig. 3b but for cloud fraction,  $f$ .

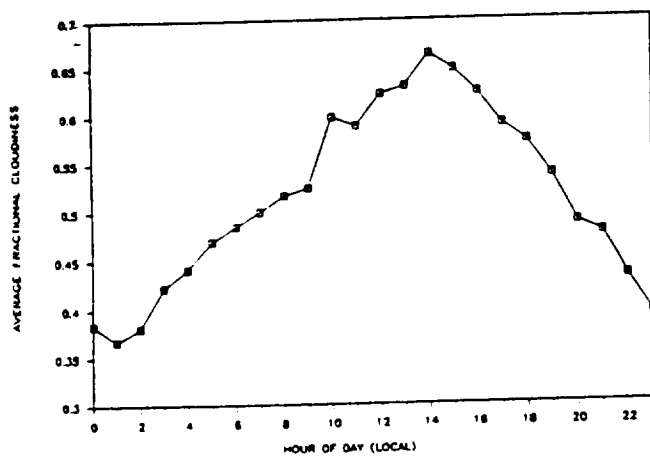


Fig. 4a. Average diurnal variation (using local time) for fractional cloudiness, derived from the longwave irradiance, during the three summer months.

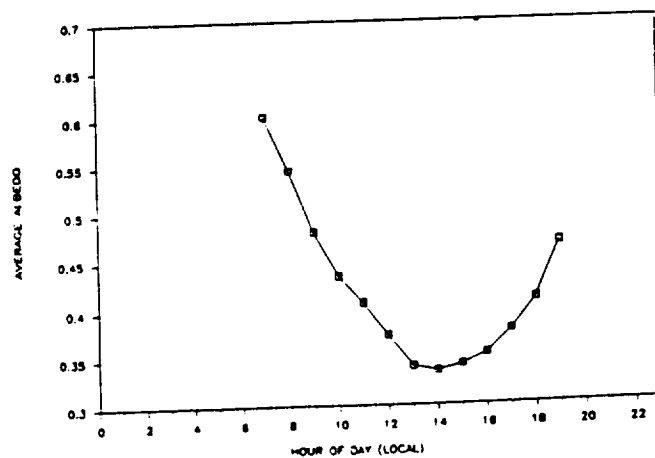


Fig. 4b. As in Fig. 4a but using shortwave irradiance derived values of cloud albedo.

